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Space Launch System

Lattice Boltzmann Method for Spacecraft Propellant Slosh Simulation

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Introduction

- **Microgravity propellant dynamics continue to offer a formidable modeling challenge for the computational fluid mechanics community**
  - Analytical approaches to prediction of bulk behavior, e.g. tank forces and moments, degrades in accuracy below *Bo*~10; small perturbations only
  - Flows dominated by surface tension; curved interfaces; fluid-wall contact angles approximately zero
  - Many semi-analytical or empirical methods that correlate well with theory rely on quasi-steady-state parameters and cannot accurately predict effects of transient flows, e.g. throttling, thruster pulses
  - Momentum transfer due to fluid must be computed accurately for simulation-based verification
- **Our research explores the applicability of the lattice Boltzmann method (LBM) to modeling of cryogenic propellant dynamics in microgravity**

The Lattice Boltzmann Method

- **The lattice Boltzmann method (LBM) is an emerging approach to CFM using an explicit temporal and spatial discretization of the continuous Boltzmann equation:**

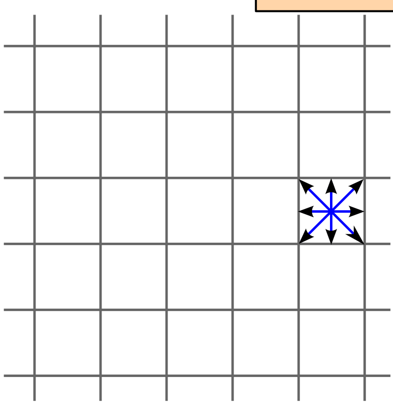
$$\frac{\partial f}{\partial t} + \xi^T \nabla_{\mathbf{x}} f + \mathbf{a}^T \nabla_{\xi} f = \Omega(f)$$

  - Describes evolution of particle distribution functions, e.g. density distribution
  - Regular Cartesian discretization of a 2X*D* position-velocity phase space on a lattice
  - In discrete form, the lattice Boltzmann equation is given by

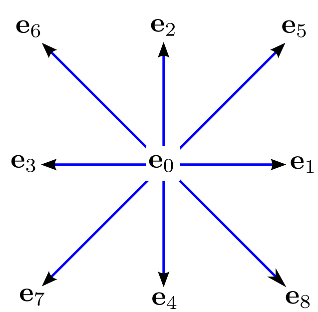
$$\mathbf{f}(\mathbf{x}_k + \mathbf{e}\delta t, t_0 + \delta t) = \mathbf{f}(\mathbf{x}_k, t_0) - \mathbf{A}\left(\mathbf{f}(\mathbf{x}_k, t_0) - \mathbf{f}^{\mathrm{eq}}(\mathbf{x}_k, \mathbf{u}_k, \rho(\mathbf{x}_k))\right)\delta t$$

Adjacent cell — **Next time step** — **Current cell** — **Relaxation operator** — **Equilibrium distribution**

D2Q9 Model



Spatial discretization



Velocity discretization

Conserved Moments

$$\rho(\mathbf{x}_k) = \sum_i f_i(\mathbf{x}_k)$$

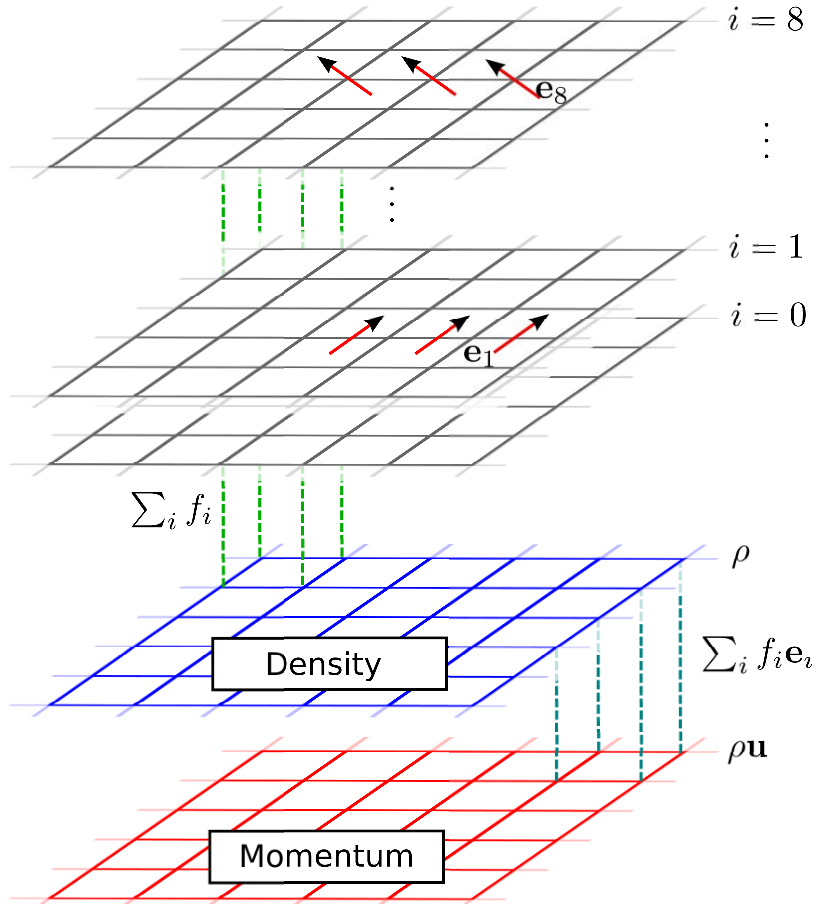
$$\rho(\mathbf{x}_k)\mathbf{u}_k = \sum_i \mathbf{e}_i f_i(\mathbf{x}_k),$$

Numerical Implementation and Limitations

- **The fluid dynamics are propagated in two steps over multiple layers**
  1. Advection (copy fluid density to adjacent cell: “streaming”)
  2. Collision (simulate collisions by relaxing toward Maxwell equilibrium: “relaxation”)

- **Proper choice of units (time=space=1) and periodic lattice: no actual data copy**
  - The streaming step is done using pointer arithmetic: *fast*
  - Data locality (only need knowledge of adjacent cells): *parallelization*

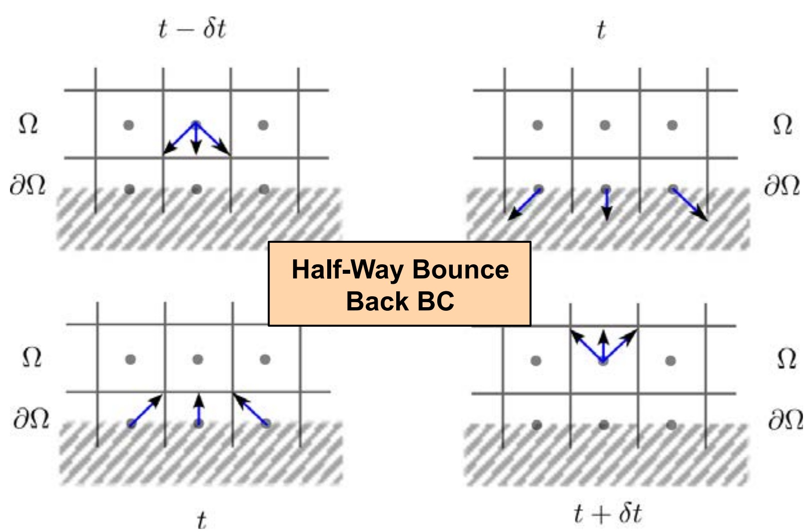
- **Limitations:**
  - Constant (wall) temperature: isothermal flow
  - Effective speed of sound is related to the lattice physical parameters
    - Compressibility error increases as *M*>0.1
    - Incompressible flow approximation is valid only for steady flow at low velocities
  - Stability *decreases* as timestep decreases at a fixed kinematic viscosity

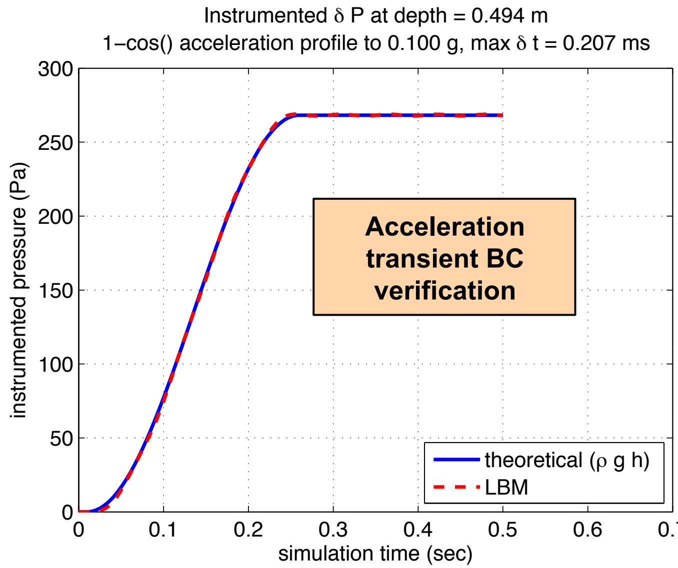


Boundary Conditions & Body Forces

- **Wall boundary conditions are straightforward to implement**
  - So-called “bounce back rule”: invert velocity distributions at boundary
  - Reconstruct unknown distributions by storing in boundary for one timestep
  - Not a hydrodynamically accurate BC, but simulates no-slip wall
  - More accurate BCs are required for free slip, walls with high curvature, inlet flow, etc.

- **Relaxation operation and body forces**
  - Body forces implemented using Kupershtokh exact difference method (EDM)
  - Shift equilibrium distribution under action of force such that lattice remains in equilibrium
  - Relaxation operation uses multiple relaxation time (MRT) scheme accounting for variation in kinematic viscosity with optional subgrid turbulence model





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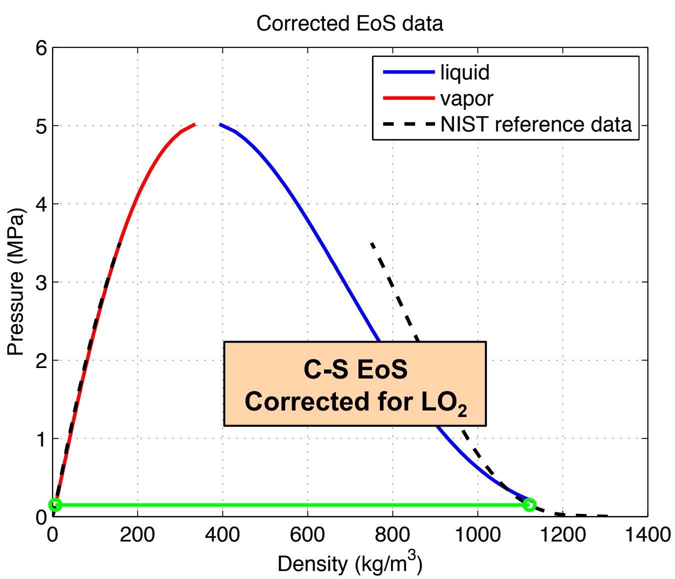
Multi-Phase Flow & Wall Wetting

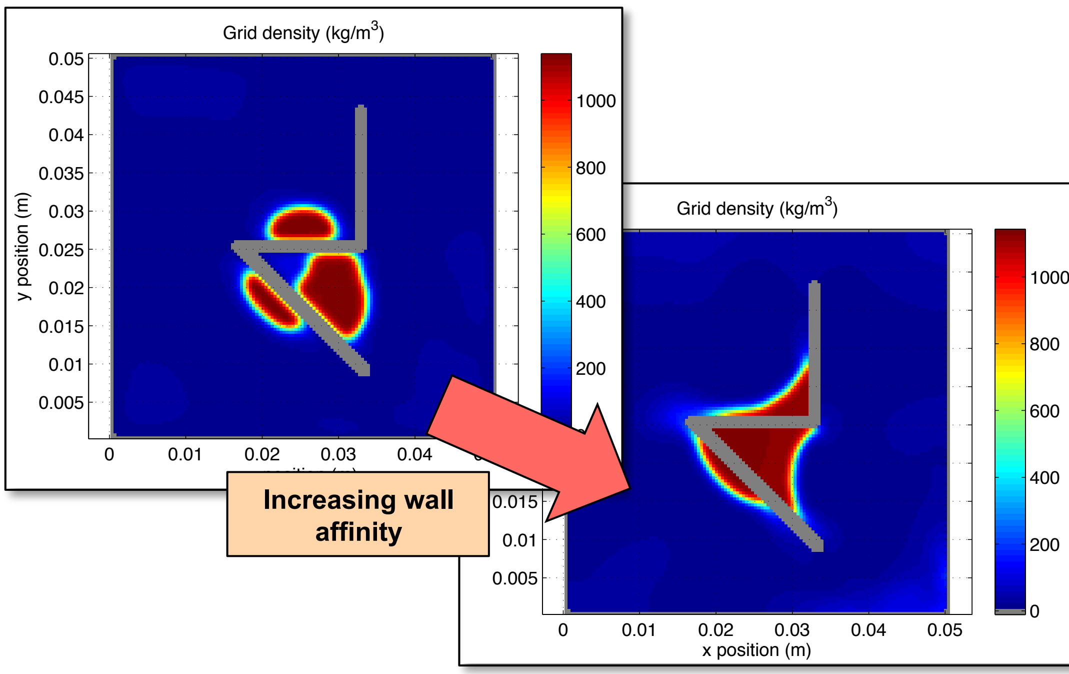
- **LBE models allow incorporation of multiple phases uniformly in the lattice**
  - Phase separation explicitly depends on temperature and a real gas EoS
  - We use the Carnahan-Starling EoS corrected for the target conditions (LO_2 @ 94K) in a Shan-Chen like pseudopotential model

$$p = \rho RT \frac{1 + b\rho/4 + (b\rho/4)^2 - (b\rho/4)^3}{(1 - b\rho/4)^3} - a\rho^2$$

  - Phase segregation approximately obeys Maxwell construction ("mechanical stability")

- **Parametric wall wetting model allows tuning of free surface contact angle**





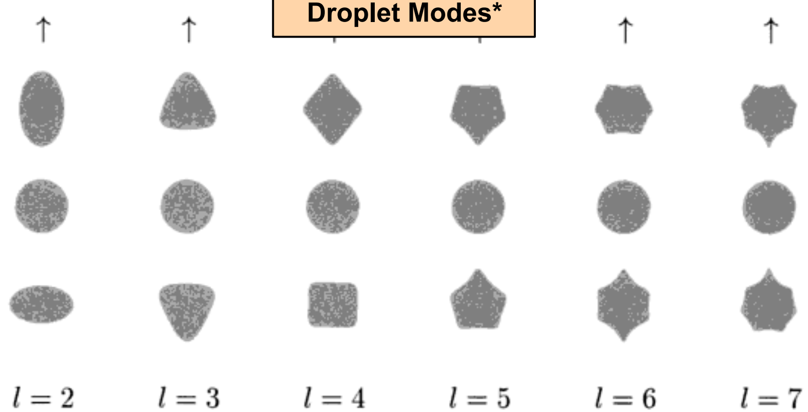
Simulating Droplet Dynamics

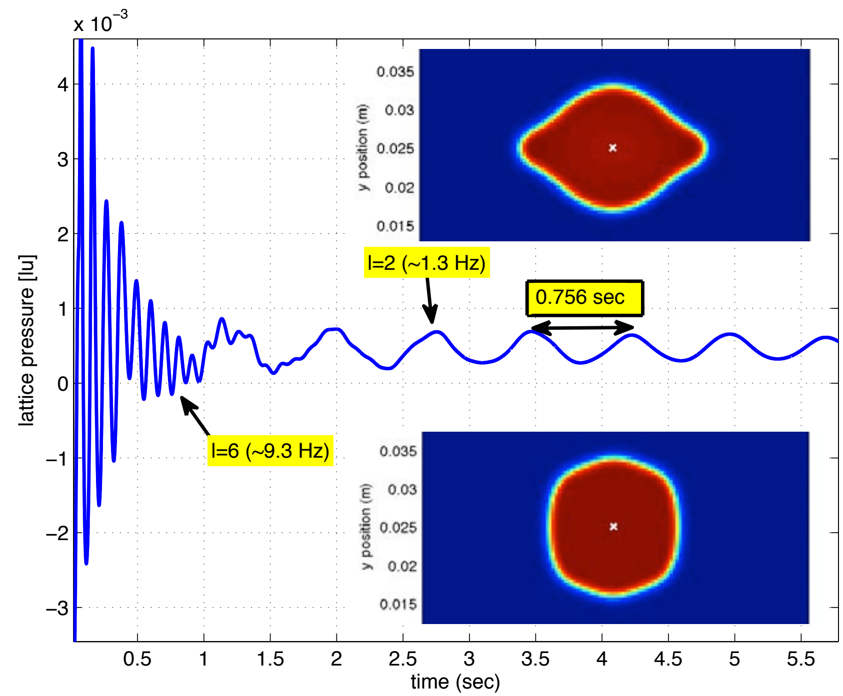
- **The behavior of droplets in microgravity is dominated by surface tension**
  - Droplet dynamics provide a useful verification case due to analytical solutions
  - Oscillation of the free surface can be predicted by Lamb's equation
  - Effective surface tension can be determined from frequency

$$\omega^2 = \frac{l(l-1)(l+2)}{r^3 \rho_L} \sigma$$

Mode frequency **Droplet radius** **Surface tension**

Droplet Modes*



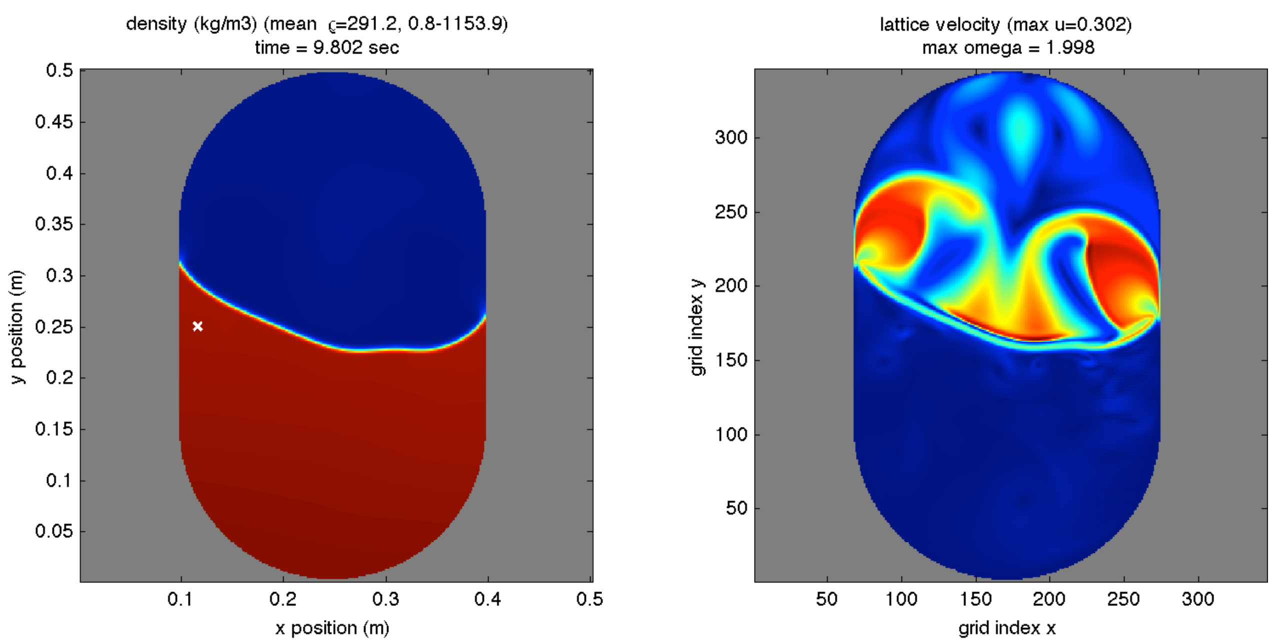


*Frohn, A., and Roth, N. Dynamics of Droplets. Springer, 2000

Propellant Slosh (Low *Bo*)

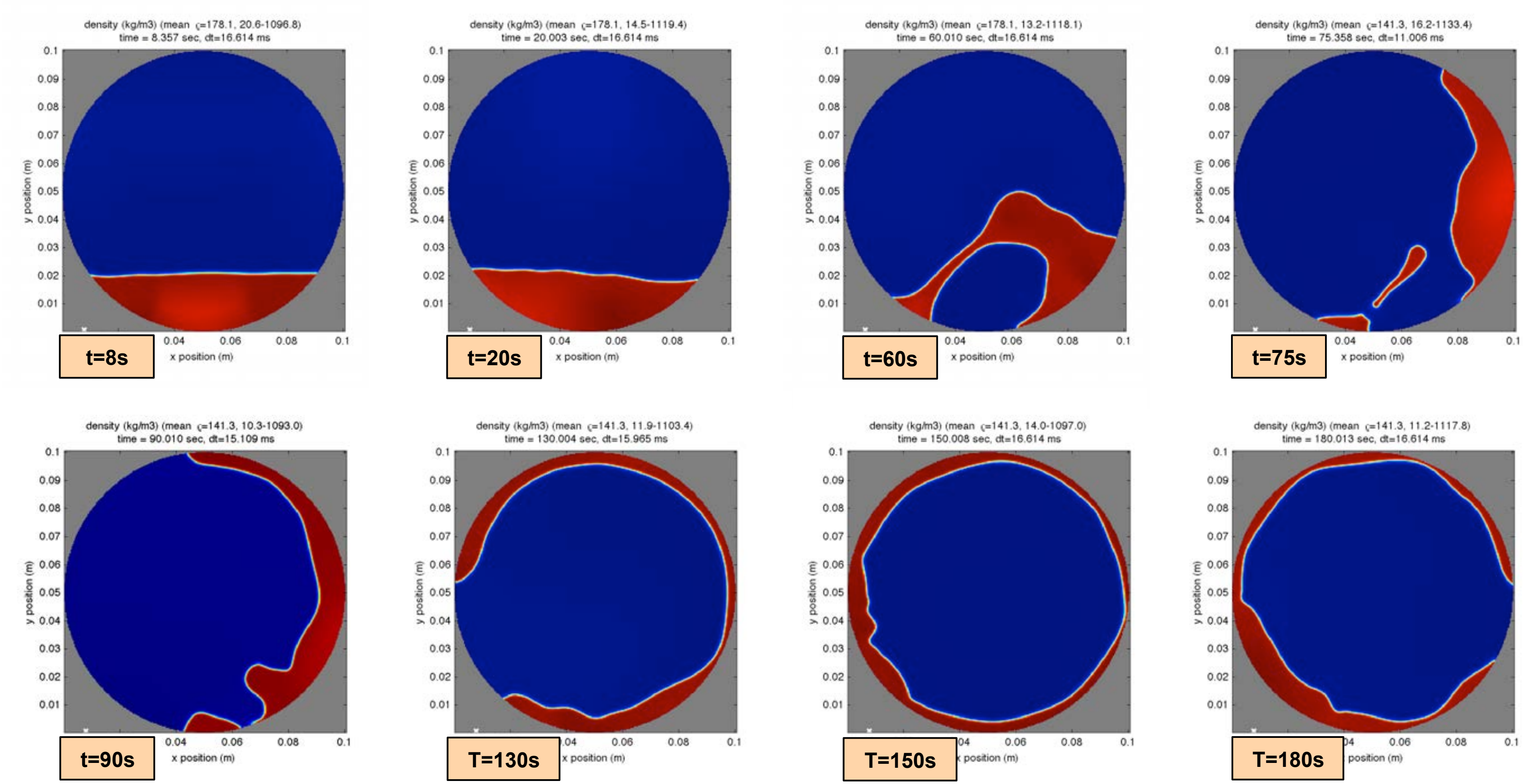
- **Propellant sloshing dynamics are of fundamental concern in spacecraft dynamics**
  - Analytical solutions exist for axisymmetric containers at high *Bo*
  - Below *Bo*=1000 modified analytical models must be used
    - Stable flow only (continuous free surface) and small perturbations
  - CFD solutions required for turbulent flow, transient phenomena, PMD simulation, etc.

- **LBE method verified using a flow regime near analytical limit**
  - 0.15 m cylindrical LO_2 tank with hemispherical ends @ 0.001 g (*Bo*=20)
  - Lattice size = 346^2 (4.1 MB)
  - Free decay from initial condition with acceleration 15 degrees from symmetry axis
  - First mode frequency matches analytical predictions very well (*f*=0.055 Hz)



Fluid Slosh (Microgravity)

- **LBM approach used for small domain simulation in microgravity**
  - 0.1m spherical LO_2 container in microgravity
  - High-g initial condition (settled fluid) and 0g at t=0 (20% fill fraction)
  - Random perturbing acceleration (-3 dB @ 0.2 Hz, g_{RMS}=0.00003)
  - Lattice size = 266^2 (2.4 MB)



Forward Work

- **Some promising results have been obtained in the application of the LBE to propellant sloshing dynamics and related microgravity fluid phenomena**
  - The LBE method has promise for simulation of thermodynamically consistent multiphase flows in cryogenic propellants
  - Fundamental stability limitations remain for very low kinematic viscosities (real fluids!)
  - Recent progress includes stability enhancement via adaptive time-stepping and improvement in surface tension model using multirange pseudopotential
    - Overcomes some stability and surface tension limitations by improving isotropy

- **Production simulation of cryogenic flows will require incorporation of thermal effects**
  - Thermal LBE codes are emerging and show some promise
  - Important to capture convective phenomena, for example, for modeling of long-term fluid circulation in propellant storage systems

- **Ongoing work extends the present proof-of-concept model to a 3D code**
  - Parallelization opportunities may allow simulation of CFD-in-the-loop with spacecraft GN&C 6-DoF simulations, for example, using GPU computing
  - Possible validation opportunities using existing microgravity fluid experiment data collected aboard International Space Station (ISS)
  - 3D code targeted for NASA Exploration Upper Stage (EUS) ullage settling and propellant management studies